Effect of the pressure gradient in the connection region on the PBM stability

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Introduction

The width of the plasma edge pedestal formed by the transport barrier and the pressure at the top of the pedestal strongly affect performance of tokamak fusion plasmas. In previous studies [1, 2], the pressure gradient at the centre of pedestal was mainly considered as a major factor that determines the pedestal stability. However, the edge instabilities are non-local [3, 4] so that the pressure gradient and current profile in other regions can also affect the stability [5, 6] and the structure of the pedestal. For this reason, we have investigated the dependence of pedestal properties such as the pedestal height and the pedestal width on $\alpha_i$ which represents the pressure gradient in the connection region.

We have used a fixed boundary code, HELENA [5] to construct the plasma equilibrium and MHD stability code, MISHKA [6] to calculate the edge MHD instability. The edge predictive model EPED1 [7] was also used to predict and to understand the behaviour of the edge pedestal in terms of $\alpha_i$. Based on these results, we suggested the possible mechanism of the interaction between the edge pedestal and the core profile through Shafranov shift and $\alpha_i$.

Simulation setup

To investigate the effect of $\alpha_i$ on the edge stability, the stability analysis of the peeling-balloonning mode (PBM) [8] is carried out in terms of $\alpha_i$. We used $\alpha_i$ as normalised pressure gradient $\alpha$ [9] at $\psi_N = 0.9 \simeq 1 - 2.5W_{ped}$ for simplicity in this study, where

$$\alpha = -\frac{2\mu_0 \partial V}{(2\pi)^2} \frac{\partial \psi}{\partial \psi} \left( \frac{V}{2\pi^2 R_c} \right)^\frac{1}{2} \frac{\partial P}{\partial \psi}. \tag{1}$$

Here, $V$ is the plasma volume contained by the poloidal flux surface ($\psi$), $R_c$ is the geometric center of the poloidal flux contour, and $P$ is the plasma pressure. A JET-like discharge is selected as a reference equilibrium for the stability calculation whose major parameters are as following; major radius $R_0 = 2.91$, aspect ratio $A = 3.15$, plasma current $I_p = 1.38$ MA, toroidal field $B_0 = 1.69$ T), upper elongation $\kappa_{up} = 1.58$, lower elongation $\kappa_{low} = 1.73$, upper triangularity $\delta_{up} = 0.37$, lower triangularity $\delta_{low} = 0.36$, normalized beta $\beta_N = 2.25$, density at the top of the pedestal $n_{e,ped} = 3.36 \times 10^{19}$ m$^{-3}$, and carbon impurity with effective charge number $Z_{eff} = 1.36$. We used the same
and boundary shape as the reference while pressure profiles were adjusted to change $\alpha_i$ while keeping 
the current density and pressure profiles in the pedestal region fixed to remove their effect on the PBM 
stability. To modify the pressure profile, we used temperature and density profile form as Eq. (2)

$$T(\psi_N) = \alpha_{t1} \left( 1 - \frac{\psi_N}{1 - W_{ped}} \right)^{\beta_{t1}} H(\psi_N - 1 + W_{ped}) + \alpha_{t2} \tanh \left( \frac{2(\psi_N - 1 + W_{ped}/2)}{W_{ped}} \right) + \alpha_{t0}. \quad (2)$$

In Eq. (2), $W_{ped}$ is the pedestal width in the normalized poloidal flux coordinate ($\psi_N$) set to be 0.04, $H$ 
is the unit step function, $\alpha_{t0}$ is the temperature at the separatrix, and the first and the second term 
describe the core and the pedestal profile, respectively. The electron density profile, $n_e(\psi_N)[10^{19} m^{-3}]$ 
was defined in the same form as Eq. (2) with $\alpha_{n0} = 0.8$, $\alpha_{n1} = 3.6$, $\alpha_{n2} = 1.4$, $\beta_{n1} = \beta_{n2} = 1.1$. 
Lastly, $T = T_e = T_i$ is assumed and the current profile was constructed with the Sauter’s bootstrap 
current model with Ohmic contributions [10]. We reconstructed the plasma equilibrium and calculated 
the PBM stability under these conditions.

**Effect of $\alpha_i$ on the PBM stability**

To calculate the effect of $\alpha_i$ on the growth rate of PBM, we produced four equilibria, where $\alpha_i$ 
changes from 0.5 to 0.8 (see Fig.1). We controlled $\alpha_{t1}$ and $\beta_{t2}$ of the temperature profile in Eq. (2) 
to adjust $\alpha_i$ while other plasma parameters including Shafranov shift and $\alpha$ profile in the 
pedestal region were fixed. Results of the stability calculation are shown in Fig. 2. As $\alpha_i$ increases, 
PBM is destabilised and the growth rate increases for all $n$ values. For example, the growth rate of $n = 12$ has increased from 0.042 to 0.05 as $\alpha_i$ changes from 0.5 to 0.8. To understand the effect of $\alpha_i$, we 
examined the variation of mode structure according to $\alpha_i$. Figure 3 shows the mode structure or

**Figure 1.** Profiles of (a) pressure, (b) current, safety factor, and (c) magnetic shear ($\|\)$. The gold, green, red and 
blue lines show the profiles in cases whose $\alpha_i$ values are 0.5, 0.65, 0.75, and 0.8, respectively.

**Figure 2.** Growth rate ($\gamma/\omega_p$) of PBM versus the mode number. Gold, green, red, and blue lines 
are for $\alpha_i = 0.5, 0.65, 0.75, \text{ and } 0.8$, respectively.
eigenfunction of \( n = 5 \) (Fig. 3(a)), \( n = 15 \) (Fig. 3(b)) and \( n = 25 \) (Fig. 3(c)) for two equilibria, one with \( \alpha_i = 0.65 \) (green) and the other with \( \alpha_i = 0.8 \) (pink). The width of the mode is shown to increase with \( \alpha_i \). As the amplitude of the mode in the connection region increases, width of the mode envelope becomes wider. When \( \alpha_i \) increases, the ballooning component in the connection region becomes destabilized due to increase in the pressure gradient and consequently, the relative amplitude of the mode increases. Since PBM components in the connection region and the edge regions are coupled, increase in the mode component at the inner region can result in destabilization of PBM.

Destabilising effect of \( \alpha_i \) on PBM depends on the mode number \( n \) as shown in Fig. 2. When \( \alpha_i \) changes from 0.5 to 0.8, PBM growth rate with intermediate \( n \) tends to be more affected by \( \alpha_i \) than that with lower and higher \( n \). For low \( n \) cases where the peeling part is dominant, the peeling component whose destabilizing source is the pedestal current density is less likely to be affected by \( \alpha_i \), since \( \alpha_i \) is the destabilizing source of the ballooning component. For high \( n \) cases (\( n=25 \)), the width of the mode envelope of PBM is smaller than lower \( n \) modes (\( n=5, 15 \)) in Fig.3. As the PBM component in the connection region normalized to its maximum near the edge is already small in higher \( n \), the effect of \( \alpha_i \) in this region is also small. Therefore, coupling between the connection region and the edge region is relatively reduced for high \( n \). For this reason, the stability of PBM can be less sensitive to \( \alpha_i \) in high \( n \) PBM. It can be also found in Fig.3 that the mode structure of \( n=25 \) is less sensitive to \( \alpha_i \) than that of \( n=5 \) and \( n=15 \).

**Effect of \( \alpha_i \) on the pedestal structure**

To understand the effect of \( \alpha_i \) on the pedestal structure, we applied EPED1 to the edge predictive analysis. Here, we changed not only \( \alpha_i \) but also Shafranov shift \( \Delta'_{ped} \) to investigate their effect on the edge pedestal together. Results from the predictive analysis is shown in Fig.4. The temperature \( (T_{ped}) \) at pedestal top which is predicted by EPED is drawn on the contour where x- and y- axis correspond to \( \Delta'_{ped} \) and \( \alpha_i \), respectively.
EPED analysis on the reference equilibrium shows that $T_{ped}$ improves with $\Delta'_{ped}$ while it deteriorates as $\alpha_i$ increases. For example, when $\Delta'_{ped}$ changes from 0.3 to 0.33, $T_{ped}$ increases by 13%. This behaviour of $T_{ped}$ is due to the stabilization of PBM by $\Delta'_{ped}$. It is also consistent to the previous studies [11-12]. When $\alpha_i$ increases from 0.4 to 0.55, $T_{ped}$ decreases by 15% as shown in Fig. 4. The effect of $\alpha_i$ on $T_{ped}$ is also related to the destabilising effect of $\alpha_i$ on PBM. Furthermore, we expect that the edge pedestal whose MHD stability is peeling- or ballooning- dominant will be less affected by $\alpha_i$ as PBM with low and high $n$ are less sensitive to $\alpha_i$.

**Conclusion**

In this study, we analysed the effect of the pressure gradient in the connection region on the edge MHD stability. We compared the PBM stability of various equilibria with different $\alpha_i$, and found that large $\alpha_i$ destabilizes PBM. The mode structure widens as $\alpha_i$ increases. Destabilization of PBM with $\alpha_i$ was related to the increment of the destabilizing source of the pressure gradient in the connection region and coupling between the connection region and the edge region. Also, decrease of $\tilde{s}$ in the connection region due to increase in the bootstrap contribution to $j_\phi$ with $\alpha_i$ further acts to destabilize PBM. The EPED prediction shows that as $\Delta'_{ped}$ increases or as $\alpha_i$ decreases, the pedestal height improves. This is because the PBM stability has improved allowing enhancement of the edge pedestal. This highlights the importance of modelling the core accurately when the pedestal is predicted as increasing the core pressure can either decrease (through $\alpha_i$) or increase (through $\Delta'_{ped}$) the predicted pedestal height.

**References**

[1] N.Oyama et al., NF 50, 064014, 2010
[2] E. Stefanikova et al., NF 58, 056010, 2018